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**AFOSR-AASSERT**

**“Optical and Electrical Investigations of Widegap Nitrides for  
Applications in Epitaxial Growth Devices”**

**Final Report for**

**Sept. 1, 1995—August 31, 1998**

**P.I.: Dr. Jin-Joo Song  
Center for Laser and Photonics Research  
Department of Physics  
413 Noble Research Center  
Oklahoma State University  
Stillwater, OK 74078-3038**

**19990818 219**

## Achievements

In this AASERT program, graduate students were trained in the area of optical and electrical investigations of wide gap III-nitride heterostructures. Students received training on experimental apparatus as shown in the following pages, including stimulated emission (SE), photoreflectance (PR), photoluminescence excitation (PLE), and pump-probe experiments. The goal of the program was to study optical and electrical properties for both epitaxial growth and photonic device applications. Blue and UV semiconductor lasers and optical modulators were of particular interest to us. During the course of the program, students actively collaborated with theoretical, MBE and MOCVD research groups from University of Illinois (Prof. Y. C. Chang and Prof. H. Morkoc), University of California, Santa Barbara (Prof. S. DenBaar), Honeywell, University of North Carolina (Prof. R. F. Davis), EMCORE and CREE.

We recorded several world first observations of:

- the first observation of stimulated emission separate confinement heterostructure AlGa<sub>N</sub>/Ga<sub>N</sub>/AlGa<sub>N</sub> with a single Ga<sub>N</sub> quantum well, 70Å thick:
  - Appl. Phys. Lett. 70, 868 (1996)
- the first picosecond laser four-wave-mixing experiments in Ga<sub>N</sub>:
  - Appl. Phys. Lett. 68, 587 (1996)
- the first femtosecond coherent transient spectroscopy with Ga<sub>N</sub> excitons:
  - Rev. B 56, 1 (1996)
- the first high temperature stimulate emission observation in Ga<sub>N</sub>(up to 700K) and InGa<sub>N</sub>/Ga<sub>N</sub> MQWs (up to 550K):
  - Appl. Phys. Lett. 72, 1623 (1998); J. Appl. Phys., 85, 1792 (1999).
- the first observation of lasing in Ga<sub>N</sub> micropiramids grown on patterned Si by selective area overgrowth:
  - Appl. Phys. Lett. 73, 2242 (1998)
- the first pump-probe laser experiments for induced gain in Ga<sub>N</sub> and InGa<sub>N</sub>/Ga<sub>N</sub> MQWs
  - Appl. Phys. Lett. 72, 1504 (1998); Appl. Phys. Lett. 73,1370 (1998)

- the first systematic study of Si-doping effects on MOCVD InGaN/GaN MQWs:  
-- Appl. Phys. Lett, 73, 1128 (1998).

This award also resulted in two Ph.D. theses in the Department of Physics: "Optical Spectroscopy of Highly Excited Group III Nitrides" by Theodore Schmidt, and "Ultrafast Carrier Dynamics of Wide Gap Semiconductors studied via Four-wave-mixing and Pump-Probe Spectroscopies" by Arthur Fischer. Additionally, students made numerous presentations at national and international conferences; the abstracts of refereed publication and conference presentations resulting from the AASERT award follow this report.

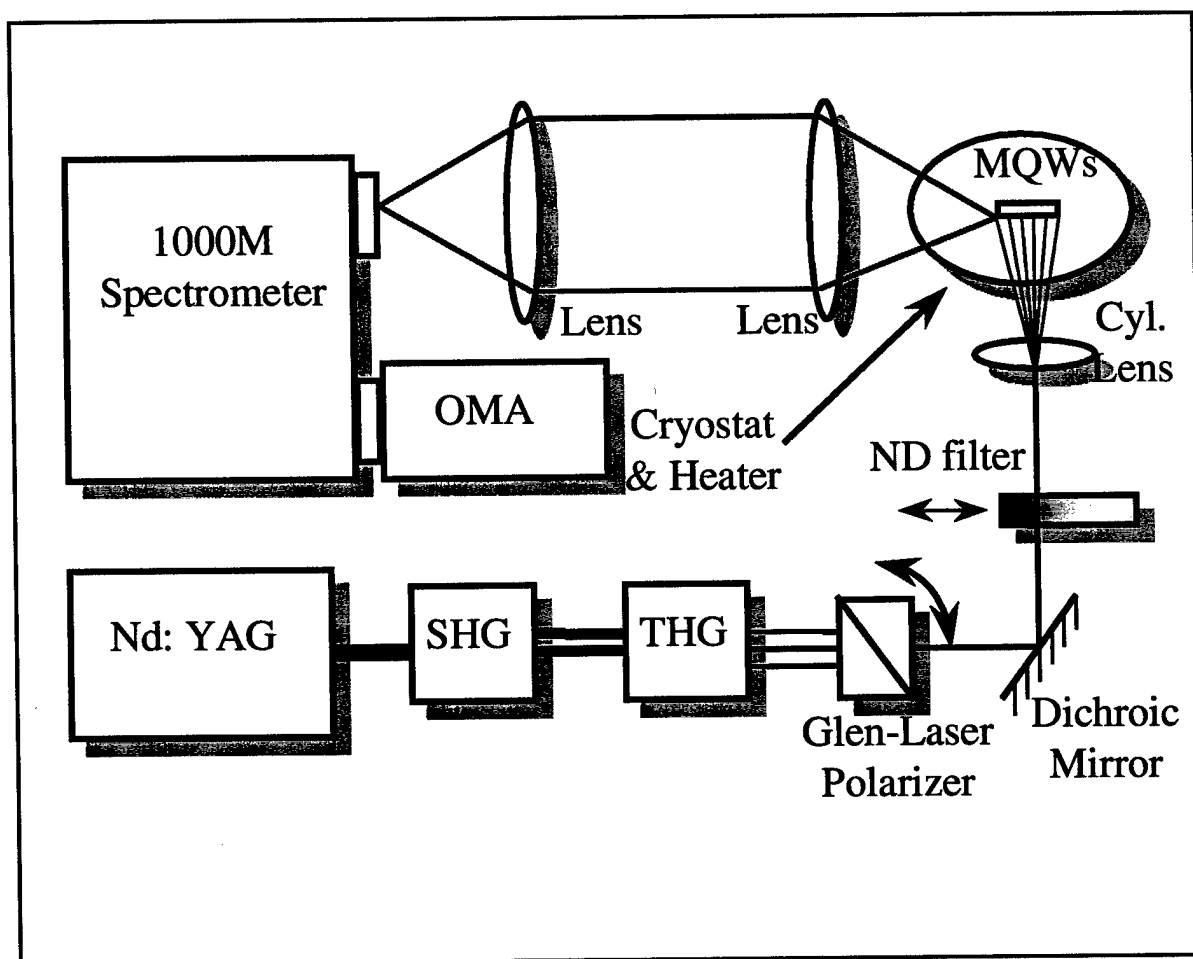


Fig. 1. Schematic diagram of stimulated emission (SE) experimental setup

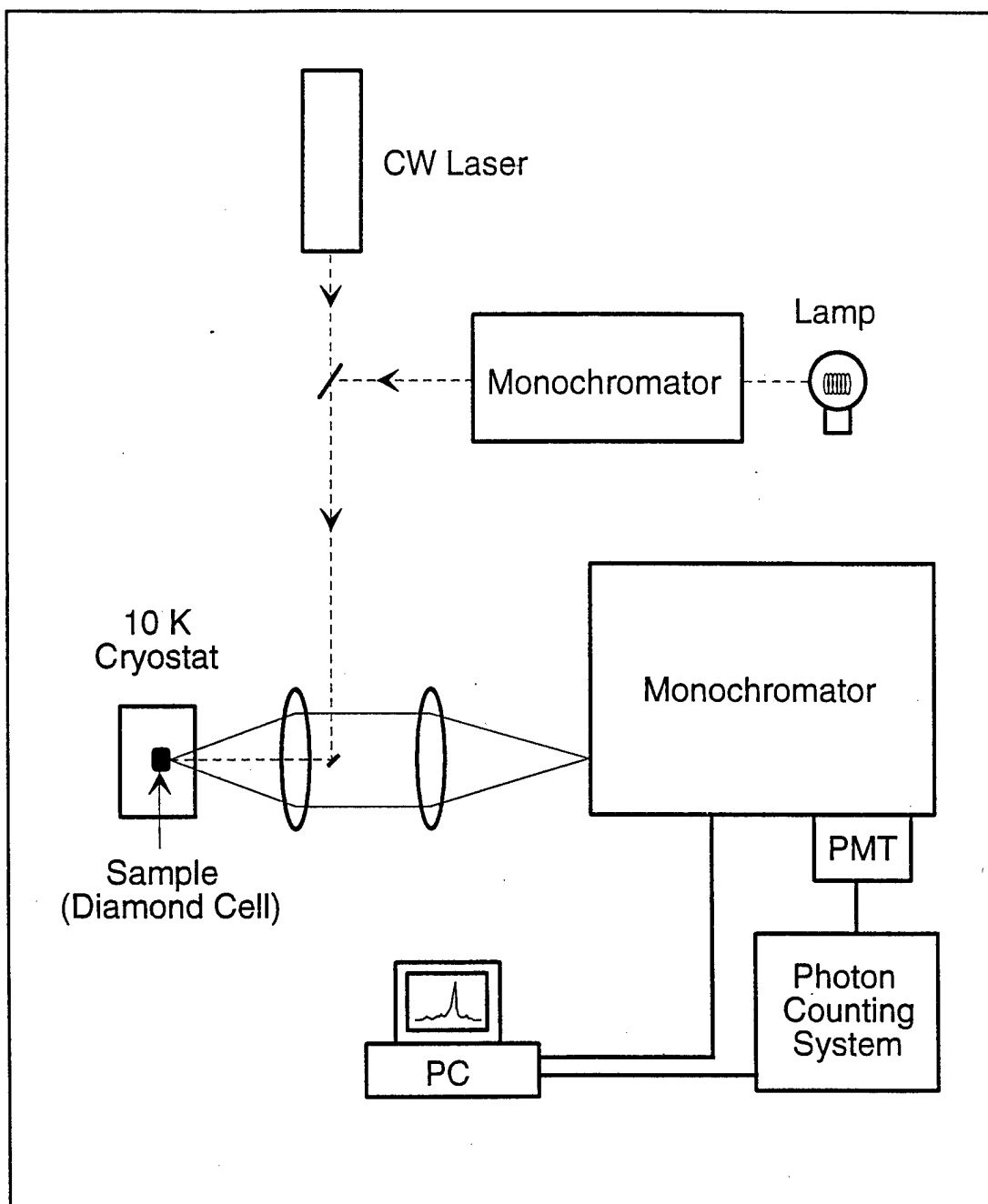


Fig. 2. Schematic diagram of photoluminescence (PL) and photoluminescence excitation (PLE) experimental setup

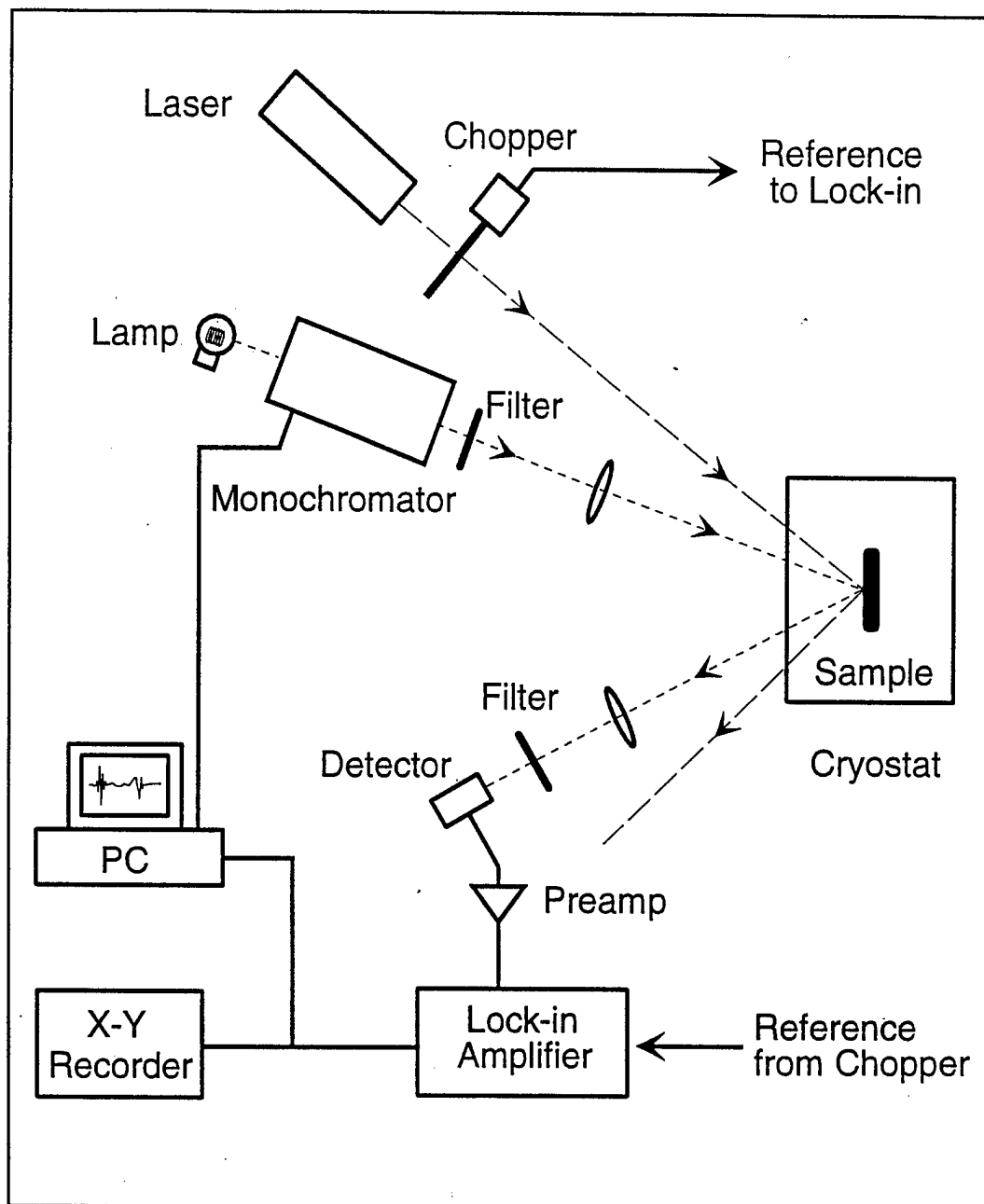


Fig. 3. Schematic diagram of photorefectance (PR) experimental setup

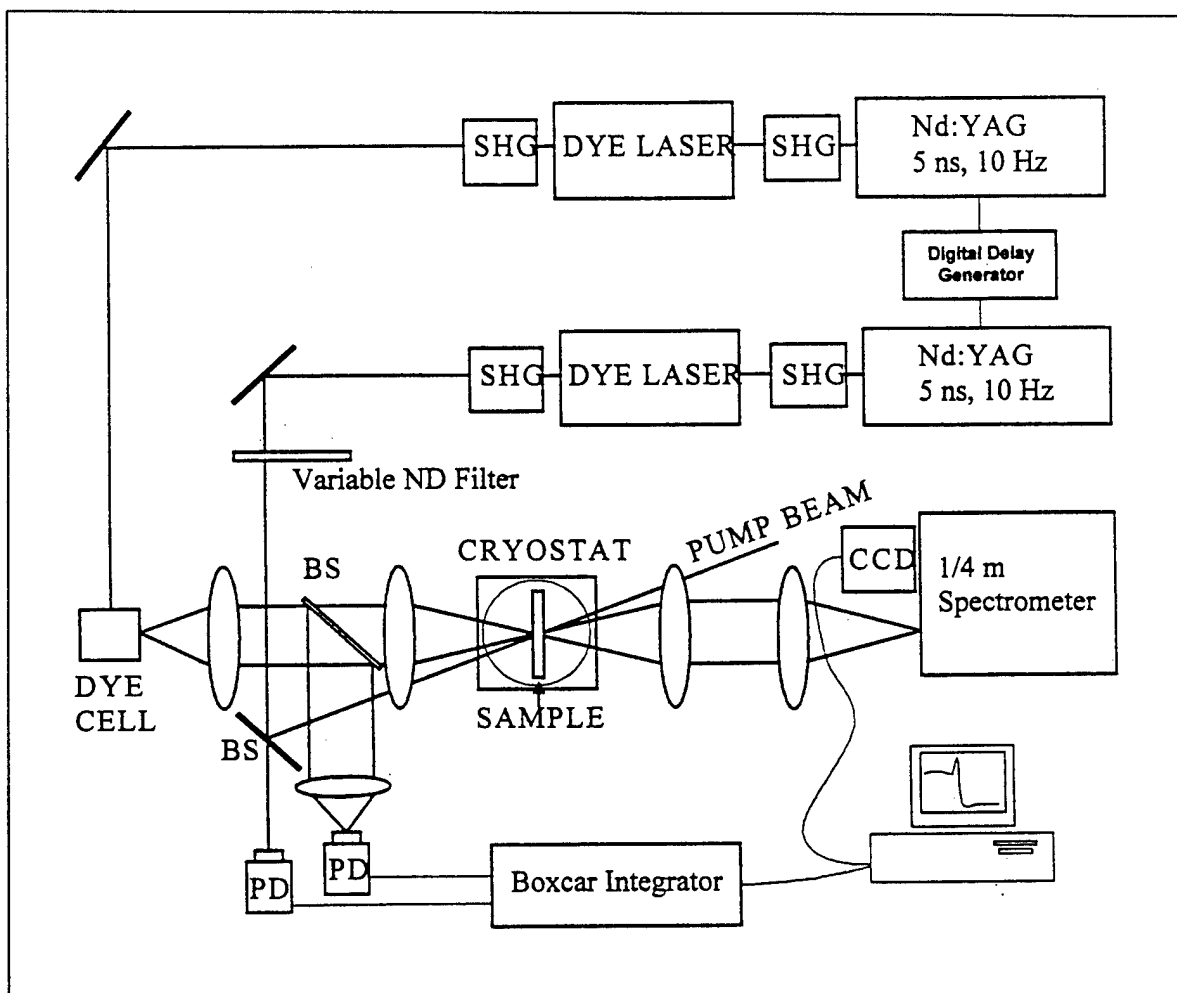


Fig. 4. Schematic diagram of pump-probe experimental setup



Conference Abstracts  
1999-1995

**"Carrier Recombination Dynamics of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  Epilayers Grown by MOCVD,"** Yong-Hoon Cho, G. H. Gainer, J. Lam, J. J. Song, W. Yang, and S. A. McPherson, MRS Meeting, Spring '99, San Francisco.

We have systematically studied the optical characteristics of MOCVD-grown AlGa<sub>N</sub> epilayers by means of photoluminescence (PL), PL excitation, and time-resolved PL spectroscopy. AlGa<sub>N</sub> epilayers with Al mole fraction ( $x$ ) ranging from 0 to 0.6 were investigated. We observed anomalous temperature-induced emission shift behavior for AlGa<sub>N</sub> epilayers with  $x > 0.2$ , specifically an S-shaped (decrease-increase-decrease) temperature dependence of the peak energy with increasing temperature. The temperature-dependent emission behavior was enhanced as the Al mole fraction was increased. To elucidate the mechanism of the emission, integrated PL intensity and recombination decay time were investigated as a function of temperature. Radiative recombination is observed to dominate up to higher temperatures with increasing Al content in the epilayers. We demonstrate that the anomalous temperature-induced PL shift is caused by a change in the carrier dynamics with increasing temperature due to alloy fluctuation in the AlGa<sub>N</sub> epilayers. A comparison with InGa<sub>N</sub> epilayer and MQWs will also be given.

**"Comparative study of the emission from highly excited InGa<sub>N</sub>, Ga<sub>N</sub>, and AlGa<sub>N</sub> thin films,"** B. D. Little, T. J. Schmidt, J. J. Song, S. Keller, U. K. Mishra, S. P. DenBaars, and W. Yang, MRS Meeting, Spring 1999, San Francisco.

The optical properties of InGa<sub>N</sub>, Ga<sub>N</sub>, and AlGa<sub>N</sub> thin films have been studied under the conditions of strong nanosecond band to band optical excitation. A comparison of the stimulated emission properties of an  $\text{Al}_{0.17}\text{Ga}_{0.83}\text{N}$  and an  $\text{In}_{0.18}\text{Ga}_{0.82}\text{N}$  thin film to that of Ga<sub>N</sub> thin films is given. The incorporation of aluminum into Ga<sub>N</sub> is shown to result in AlGa<sub>N</sub> thin films with similar stimulated emission properties to that of Ga<sub>N</sub>, while the incorporation of indium into Ga<sub>N</sub> is shown to result in InGa<sub>N</sub> films with markedly different stimulated emission properties. The origin of these differences will be discussed. Optically pumped stimulated emission has also been studied from AlGa<sub>N</sub> films with relatively high aluminum content. Room temperature stimulated emission at wavelengths as low as 327 nm has been observed, illustrating that AlGa<sub>N</sub> is not only a suitable material for deep ultraviolet detector development, but is also suitable for the development of deep ultraviolet laser diodes.

**"Study of Near-threshold Gain mechanisms in MOCVD-grown (In, Al)Ga<sub>N</sub> Epilayers and Heterostructures,"** S. Bidnyk, T. J. Schmidt, B. D. Little, J. J. Song, MRS Meeting, Spring 1999, San Francisco.

We report the results of an experimental study on near-threshold gain mechanisms in optically pumped (In, Al)Ga<sub>N</sub> epilayers and heterostructures at temperatures as high as 700 K. We show that the dominant near-threshold gain mechanism in Ga<sub>N</sub> epilayers is

inelastic exciton-exciton scattering for temperatures below  $\sim 150$  K, characterized by band-filling phenomena and a relatively low stimulated emission (SE) threshold. An analysis of both the temperature dependence of the SE threshold and the relative shift between stimulated and band-edge related emission indicates electron-hole plasma is the dominant gain mechanism for temperatures exceeding 150 K. The dominant mechanism for SE in InGaN epilayers and InGaN/GaN multiple quantum wells was found to be recombination of carriers localized at potential fluctuations resulting from nonuniform indium incorporation. The SE spectra from InGaN epilayers and multiple quantum wells were comprised of extremely narrow emission lines and no spectral broadening of the lines was observed as the temperature was raised from 10 K to over 550 K. Based on the presented results, we suggest a method for significantly reducing the carrier densities needed to achieve population inversion in GaN, allowing for the development of GaN-active-medium laser diodes which operate at room temperature.

**"Nondegenerate optical pump-probe spectroscopy of highly excited group III nitrides,"** T.J. Schmidt, J.J. Song, S. Keller, U.K. Mishra, S.P. DenBaars, and Wei Yang, MRS Meeting, Spring 1999, San Francisco.

Nondegenerate optical pump-probe absorption experiments have been performed on GaN and InGaN thin films and quantum wells under the conditions of strong optical band to band excitation. The evolution of the band edge in these materials was monitored as the number of photo-excited free carriers was increased beyond that required to achieve population inversion and observe stimulated emission. The band edge of InGaN is shown to exhibit markedly different high excitation behaviour than that of GaN, explaining in part the reduction in stimulated emission threshold that typically accompanies the incorporation of indium into GaN to form InGaN. A comparison of the changes in band edge absorption observed in pump-probe experiments to the gain spectra measured in variable-stripe gain experiments will be given. The implications of this study on the potential for GaN-based ultraviolet laser diode development will also be discussed.

**"Room temperature deep ultraviolet stimulated emission from MOCVD-grown AlGaIn thin films on sapphire,"** T. J. Schmidt, Y. H. Cho, J. J. Song, W. Yang, APS Spring Meeting '99, Atlanta, Georgia.

Room-temperature deep-ultraviolet-stimulated emission (SE) has been observed from optically pumped metalorganic chemical vapor deposition grown  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  thin films. SE has been observed for Al concentration as high as  $x=0.26$ , with a resultant SE wavelength as low as 328 nm at room temperature. The results obtained for the  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  layers are compared with  $\text{In}_x\text{Ga}_{1-x}\text{N}$  layers of comparable alloy concentration and GaN reference layers. The incorporation of Al into layers comparable alloy concentration and GaN reference layers. The incorporation of Al into GaN is shown to result in  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  layers with similar high excitation-density emission behavior as GaN, in contrast to  $\text{In}_x\text{Ga}_{1-x}\text{N}$  layers, which exhibit markedly difference SE behavior. The observation of room-temperature SE from  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  layers of significant Al concentration illustrates the suitability of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  based structures, not only for use in deep-ultraviolet detectors, but also as a potential source of deep-ultraviolet laser radiation.

**"Excitation wavelength dependence of stimulated emission from AlGa<sub>N</sub> epilayers,"** B. D. Little, T. J. Schmidt, Y. H. Cho, G. H. Park, J. J. Song, W. Yang, APS March Meeting, Spring 1999, Atlanta, Georgia.

The characteristics of stimulated emission (SE) from AlGa<sub>N</sub> epilayers have been studied as a function of excitation wavelength at 10 K and room temperature. Samples used in this study were metal-organic chemical vapor deposition grown AlGa<sub>N</sub> layers with varying aluminum concentrations. The SE characteristics were monitored as the excitation wavelength was varied across the fundamental band edge of the AlGa<sub>N</sub> films using a tunable UV laser excitation source. The effect of tuning the excitation wavelength across the near band edge region on the emission spectra and SE threshold of the samples will be presented. The observed high excitation density behavior will be explained in conjunction with results from photoluminescence (PL), PL excitation, and time-resolved PL experiments. The results of this study will be compared with those obtained from high quality Ga<sub>N</sub> and InGa<sub>N</sub> thin films of comparable alloy composition.

**"Novel technique for evaluation of optical confinement in (In, Al) Ga<sub>N</sub> heterostructures through spatially and spectrally resolved edge-emitted stimulated emission,"** S. Bidnyk, T. J. Schmidt, J. J. Song, APS Meeting, March 1999, Atlanta, Georgia.

We present an experimental study of the effects of increasing optical confinement on the mode structure and carrier competition of stimulated emission (SE) and lasing in (In, Al) Ga<sub>N</sub> heterostructures. The edge-emitted near-field pattern of SE/lasing was imaged and spectrally resolved using a high-magnification optical assembly in conjunction with a sub-micron resolution positioning system. SE/lasing spectra were found to be strongly dependent on the position of collection optics relative to the active region. Spectral narrowing of the emission with increasing amplification path length was measured and compared with that obtained in variable stripe gain experiments. The information on the degree of optical confinement and interface roughness has been extracted through the analysis of spatially resolved high-excitation density emission spectra. We demonstrate that both the thickness of the active layer and near-band edge dispersion of the refractive index significantly affect the degree of optical confinement and emission spectra as well as the SE/lasing threshold. The implications of the study on the design of Ga<sub>N</sub>-based laser diodes will be discussed.

**"Carrier dynamics of abnormal temperature-dependent emission shift in MOCVD-grown InGa<sub>N</sub> epilayers and InGa<sub>N</sub>/Ga<sub>N</sub> quantum wells,"** Y. H. Cho, B. D. Little, G. H. Gainer, J. J. Song, S. Keller, U. K. Mishra, S. P. Denbaars, MRS Fall Meeting '98, Boston, Mass.

We report temperature-dependent time-integrated and time-resolved photoluminescence (PL) studies of InGa<sub>N</sub> epilayers and InGa<sub>N</sub>/Ga<sub>N</sub> multiple quantum wells (MQWs) grown by metalorganic chemical vapor deposition. We observed anomalously specifically an S-

shaped (decrease-increase-decrease) temperature dependence of the peak energy ( $E_p$ ) for InGaN-related PL with increasing temperature (e.g. in the case of MQWs,  $E_p$  redshifts in the temperature range of 10 – 70 K, blueshifts in the range of 70-150 K, and again for 150 – 300 K with increasing temperature). The actual temperature dependence of the PL emission was estimated with respect to the band gap energy determined by photoreflectance spectra as a function of temperature. From the study of the integrated PL intensity as a function of temperature, it is found that thermion energy states within the wells is the dominant mechanism leading to the temperature-induced S-shaped PL shift is caused by a change in inhomogeneity and carrier localization in the InGaN layers.

**“Influence of Si doping on carrier localization of MOCVD-Grown InGaN/GaN multiple quantum wells,”** Y. H. Cho, T. J. Schmidt, S. Bidnyk, J. J. Song, S. Keller, U. K. Mishra, S. P. Denbaars, MRS Fall Meeting '98, Boston, Mass.

We have systematically studied the influence of Si doping on the optical characteristic of InGaN/GaN multiple quantum wells (MQWs) using photoluminescence (PL), PL excitation (PLE) and time resolved PL spectroscopy combined with studies of optically pumped stimulated emission (SE) from these materials. The MQWs were grown on 1.8  $\mu\text{m}$ -thick GaN on c-plane sapphire films by metalorganic chemical vapor deposition. Structures consist of 12 MQWs with 30nm-thick  $\text{In}_{0.2}\text{Ga}_{0.8}\text{N}$  wells, 4.5-nm thick GaN barriers, and a 0.1- $\mu\text{m}$ -thick  $\text{Al}_{0.07}\text{Ga}_{0.93}\text{N}$  capping layer, Si doping in the GaN barriers was varied for  $1 \times 10^{17}$  to  $3 \times 10^{19} \text{ cm}^{-3}$ . Information on the structural quality of the MQWs as a function of Si doping was extracted from the linewidth broadening of the higher-order superlattice satellite peaks measured in high-resolution x-ray diffraction (HRXRD). The HRXRD measurements indicate that increased Si doping results in better interface properties of the MQWs. PL and PLE measurements show a decrease in the Stokes shift with increasing Si doping concentration. The 10 K radiative recombination lifetime was observed to decrease from  $\sim 30 \text{ ns}$  (for  $n < 1 \times 10^{17} \text{ cm}^{-3}$ ) to  $\sim 4 \text{ ns}$  (for  $n = 3 \times 10^{19} \text{ cm}^{-3}$ ) with increasing Si doping concentration. Power dependent PL studies show a strong blueshift of the spontaneous emission with increasing excitation density. The blueshift is observed to cease shortly before the onset of SE. The magnitude of this blueshift was found to decrease with increasing Si doping concentration. The reduced Stokes shift, the decrease in radiative recombination lifetime, the reduction in the observed pump-density-induced blueshift, and the increase in the interface quality with increasing Si doping indicate that Si doping results in a increase in carrier localization at potential fluctuations in the InGaN active layers.

**“Laser action in optically pumped GaN pyramids grown on (111) silicon by selective lateral overgrowth,”** S. Bidnyk, B. D. Little, Y. H. Cho, J. Krasinski, J. J. Song, W. Yang, S. McPherson, MRS Fall Meeting '98, Boston, Mass.

Laser action has been observed in GaN pyramids under the conditions of strong optical pumping at room temperature. The 15-micron-wide hexagonal-based pyramids were laterally overgrown on a patterned GaN/AlN seeding layer grown on (111) Si substrates by metal-organic chemical vapor deposition. The pattern on the seeding layer was formed

by etching 5 micron in diameter openings in  $\text{Si}_3\text{N}_4$  masking layer. The pyramids were individually pumped, imaged and spectrally analyzed through a magnification telescope system using both low-density continuous wave and high density pulsed excitation sources. At high optical pumping levels, multi-mode lasing at room temperature was observed. The integrated emission intensity for both spontaneous and lasing peaks was studied as a function of excitation power density. The cavity perimeter, finesse, and round-trip gain factors were evaluated. The effects of pyramid geometry and short-pulse excitation on the multi-mode nature of laser oscillations inside of the pyramids is discussed. Practical applications of the results for the development of light-emitting pixels and laser arrays will be given.

**"Amplification path length dependence studies of stimulated emission from optically pumped InGaN/GaN multiple quantum wells,"** T. J. Schmidt, S. Bidnyk, Y. H. Cho, A. J. Fisher, J. J. Song, S. Keller, U. K. Mishra, and S. P. Denbaars, MRS Fall Meeting '98, Boston, Mass.

Optically pumped stimulated emission (SE) from InGaN/GaN multiple quantum wells (MQWs) grown by metal organic chemical vapor deposition (MOCVD) has been systematically studied as a function of excitation length ( $L_{\text{exc}}$ ). The sample structures consist of 12-period MQWs with 3 nm thick In 0.2 Ga 0.8 N wells, 4.5 nm thick GaN barriers, and a 0.1  $\mu\text{m}$  thick  $\text{Al}_{0.07}\text{Ga}_{0.93}\text{N}$  capping layer. The  $\omega_{-20}$  scans measured by four-crystal high-resolution x-ray diffraction clearly show higher-order satellite peaks indicating high interface quality and good layer periodicity. Optically pumped SE has been observed from these structures at temperatures well above room temperature (exceeding 600 K), indicating their high optical quality. Two distinct SE peaks were observed from these structures: one that originates at 425 nm at 10 K (430 nm at 300 K) and another whose peak position at threshold originates at 434 nm at 10 K (438 nm at 300 K). The SE threshold for the high-energy peak was observed to always be lower than that of the low energy peak, but the difference was found to decrease greatly with increasing  $L_{\text{exc}}$ . A detailed study of the emission intensity of these two SE peaks as a function of excitation density shows that the two peaks compete for gain in the MQW active region. This competition is important to understand in the design of high power laser diodes, where high current densities and/or long cavity lengths can lead to a shift in the dominant gain mechanism and a resultant change in the emission behavior.

**"High-temperature stimulated emission studies of MOCVD-grown GaN films,"** S. Bidnyk, C. K. Choi, T. Schimdt, J. Krasinski and J. J. Song, Photonics '97, Taipei, Taiwan.

Edge-emitted stimulated emission (SE) in optically pumped GaN thin films was studied in the temperature range of 20 K to 700 K. The single-crystal GaN films used in this work were grown by MOCVD on (0001) sapphire and 6H-SiC substrates. We have observed that the SE peak shifts its position from 360 nm at 20 K to 420 nm at 700 K, which is the highest temperature at which SE has been reported for this material. The temperature sensitivity of the SE threshold was studied over the entire temperature range.

The characteristic temperature was found to be 180 K over the temperature range of 200 K to 700 K. The efficiency of SE generation, as well as the relative energy difference between the SE and band-edge related cw photoluminescence peaks, was analyzed over the entire temperature range. This study shows that GaN has an extremely low temperature sensitivity compared to other semiconductors and could be suitable for the development of light emitting devices that can operate significantly above room temperature. This work was supported by BMDO, ONR, AFOSR, AND DARPA.

**"High-temperature stimulated emission in optically pumped InGaN/GaN multi-quantum wells,"** S. Bidnyk, Y. H. Cho, T. J. Schmidt and J. J. Song, MRS, April 13-17 '98, San Francisco, CA.

We report the results of an experimental study on stimulated emission (SE) in optically pumped InGaN/GaN multi-quantum well (MQW) structures grown by metalorganic chemical vapor deposition in the temperature range of 175-575 K. Samples used in this work consisted of 12 MQWs grown on a 1.8  $\mu\text{m}$  thick GaN base layer. The samples had a superlattice period of  $\sim 80\text{\AA}$ . The GaN barriers were intentionally doped with a different Si concentration ranging from  $1 \times 10^{17}$  to  $3 \times 10^{19} \text{ cm}^{-3}$  and the effects of Si doping of GaN barriers on stimulated emission thresholds and photoluminescence intensities of InGaN/GaN MQWs were investigated. We observed that the SE spectra were comprised of many narrow peaks of less than 1  $\text{\AA}$  full width at half maximum (FWHM). No broadening of FWHM of the peaks occurred as the temperature was raised from 175 to 575 K. The SE threshold was measured as a function of temperature and compared with that of bulk GaN. We observed that the SE threshold had a low value and a weak temperature dependence: for example,  $\sim 25 \text{ kW/cm}^2$  at 300K, and  $\sim 300 \text{ kW/cm}^2$  at 575 K for one of the samples. Low SE thresholds are attributed to high quantum efficiency of the MQWs, possibly associated with large localization of excitons. The characteristic temperature of 162 K was derived from the temperature dependence of the SE threshold. The integrated emission intensity versus pumping density was examined for different temperatures. This study shows that InGaN/GaN MQWs are suitable for development of laser diodes that can operate well above room temperature.

**"S-shaped temperature dependent emission shift and carrier dynamics in MOCVD-grown InGaN/GaN multiple quantum wells,"** Y. H. Cho, G. H. Gainer, A. J. Fischer, J. J. Song, S. Keller, U. K. Mishra and S. P. DenBaars, Meeting of the American Physical Society, March '98, Los Angeles, CA.

We report temperature dependent photoluminescence (PL) studies of InGaN/GaN multiple quantum wells (MQWs) using time-integrated and picosecond time-resolved PL techniques. We observed anomalous emission behavior, the so-called S-shaped (i.e. decreasing-increasing-decreasing) temperature dependence of the peak energy for the InGaN-related PL with increasing temperature. To elucidate the origin of this behavior, the integrated PL intensity and carrier lifetime were investigated as a function of temperature. The results suggest that the InGaN related emission is significantly affected by the change in carrier dynamics with increasing temperature, possibly arising from

large exciton localization effects in the InGaN/GaN MQW's. This work was supported by AFPSR, ONR, and ARO.

**"Femtosecond four-wave-mixing in GaN in the excitonic region," A. J. Fischer, W. Shan, G. H. Park, J. J. Song, D. S. Kim, R. Horning and B. Goldenberg, ICNS, October 27-31 '97, Tokushima, Japan.**

Femtosecond four-wave-mixing (FWM) measurements are performed on excitons in GaN epilayers. The dominant contribution to the GWM signal is shown to be due to the A and B free excitonic resonances with negligible contribution from continuum states. Spectrally-resolved FWM data are compared to time-integrated FWM measurements to show that the excitonic resonances are nearly homogeneously broadened. The dephasing rate is measured as a function of temperature in order to determine the exciton-phonon interaction rates. A strong beating has been observed in the time-integrated FWM signal due to the interaction of the A and B excitonic resonances. The beating is shown to be due to the quantum beats rather than polarization interference. A phase change of  $\pi$  has also been observed in the quantum beating when changing from the collinear to cross linear polarization geometry.

**"Dynamics Study of Minority-carrier diffusion in  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  heterostructures," J. J. Song, W. Shan, B. D. Little, X. C. Xie, G. E. Bulman and S. Krishnankutty, ICNS, October 27-31 '97, Tokushima, Japan.**

We present the results of a time-resolved dynamic study on the minority carrier diffusion and the spontaneous lifetime of the carriers in  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  heterostructures. Carrier dynamics including generation, diffusion, spontaneous recombination, and nonradiative relaxation in the  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  double heterostructure (DH) samples were investigated by examining the time evolution of luminescence associated with the spontaneous recombination of photoexcited carriers both in the GaN active region and AlGa $\text{N}$  cladding layers. The temporal evolution of the luminescence from the GaN active layers of the DH samples was found to be governed by a carrier diffusion dominated capture process. The determination of the capture time for the carriers drift and diffusion into the GaN active region, in addition to the effective lifetimes of the spontaneous recombination for carriers in the AlGa $\text{N}$  cladding layers and the GaN active region, allows an estimation of the diffusion constants for the minority carriers in the cladding layers. Our results yield a diffusion constant of  $2.6 \text{ cm}^2/\text{sec}$  for  $\text{Al}_{0.03}\text{Ga}_{0.97}\text{N}$  and  $1.5 \text{ cm}^2/\text{sec}$  for  $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$  at 10K.

**"Strain effects on excitonic transitions in GaN," W. Shan, R. J. Haustein, A. J. Fischer and J. J. Song, March Meeting of The American Physical Society, March 17-21 '97, Kansas City, MO.**

We present the results of experimental studies of strain effects on the excitonic transitions in wurtzite GaN epitaxial layers on sapphire and SiC substrates, with the emphasis on the determination of deformation potentials. Photoluminescence and reflectance spectroscopies were performed to measure the energy positions of exciton transitions, and

high-precision X-ray diffraction measurements were conducted to examine the lattice parameters of GaN epitaxial layers grown on different substrates. Residual strain induced by the mismatch of lattice constants and thermal-expansion between GaN epitaxial layers and substrates was found to have a strong influence in determining the energies of excitonic transitions. The overall effects of the strain generated in GaN are compressive for GaN grown on sapphire and tensile for GaN on SiC substrate. The uniaxial and hydrostatic deformation potentials of wurtzite GaN were derived from the experimental results.

**"Optical studies of MOCVD InGaN alloys," B. Little, W. Shan, J. J. Song, M. Schurman, Z. C. Feng and R. A. Stall, MRS '96 Fall Mtg., Dec. 2-6 '96, Boston, MA.**

A variety of spectroscopic techniques has been used to study the optical properties of epitaxial GaN based materials grown by metalorganic chemical vapor deposition and molecular beam epitaxy. The emphasis was on the issues vital to device applications such as stimulated emission and laser action, as well as carrier relaxation dynamics. Sharp exciton structures were observed by optical absorption measurements above 300 K, providing direct evidence of the formation of excitons in GaN at temperatures higher than room temperature. Using a picosecond streak camera, the time decay of free and bound exciton emissions was studied. By optical pumping, stimulated emission and lasing were investigated over a wide temperature range up to 420 K. In addition, the optical nonlinearity of GaN was studied using wave mixing techniques.

**"Strain effects on excitonic transitions in GaN," W. Shan, R. J. Haustein, A. J. Fischer, J. J. Song, W. G. Perry, M. D. Bremser, R. F. Davis and B. Goldenberg, MRS '96 Fall Mtg., Dec. 2-6 '96, Boston, Mass.**

We present the results of experimental studies of the strain effects on the excitonic transitions in GaN epitaxial layers on sapphire and SiC substrates, with the emphasis on the determination of deformation potentials for wurtzite GaN. Photoluminescence and reflectance spectroscopies were performed to measure the energy positions of exciton transitions, and high-precision x-ray diffraction measurements were conducted to examine the lattice parameters of GaN epitaxial layers grown on different substrates. The residual strain induced by the mismatch of lattice constants and thermal-expansion between GaN epitaxial layers and substrates was found to have a strong influence in determining the energies of excitonic transitions. The overall effects of the strain generated in GaN is compressive for GaN grown on sapphire and tensile for GaN grown on SiC. The principle uniaxial and hydrostatic deformation potentials were derived from the experimental results.

**"Optical investigations of GaN and AlGaIn/GaN Heterostructures," J. J. Song, The 8<sup>th</sup> Seoul Int'l Symposium on the Physics of Semiconductors and Applications, Oct. 21-22 '96, Seoul, Korea.**



We present the results of a series of optical experiments performed in GaN and AlGaIn/GaN heterostructures, using a variety of spectroscopic techniques. Conventional absorption, reflectance, photoluminescence and photomodulation techniques were employed, as well as nonlinear four-wave-mixing and optical pumping. The samples we studied were grown on sapphire or SiC. The subjects we will present include above-room-temperature exciton transition energy and deformation potentials derived thereof. Femtosecond coherent four-wave-mixing performed at exciton resonance provides some insight into exciton phonon interaction in GaN. Finally, recent optical pumping work for UV-blue stimulated emission will be summarized.

**"Time-resolved exciton luminescence in MOCVD grown GaN,"** W. Shan, J. J. Song, B. Goldenberg, G. E. Bulman and J. A. Edmond, March Mtg. Of the Amer. Physical Society, March 18-22 '96, St. Louis, MO.

We have studied the optical properties of GaN epitaxial layers and GaN/AlGaIn heterostructures (DH) grown on SiC substrates by MOCVD. A variety of spectroscopic methods including photoluminescence and photorefectance measurements was used to study the optical transitions originated from the intrinsic free excitons and impurity-bound excitons. Transitions associated with the impurities and defects in the GaN active layer, as well as the AlGaIn cladding layers in the DH structure, were investigated and compared with those from the bulk GaN epitaxial films. Our results indicate that the optical properties of the GaN active layer in the DH structure are superior compared to those of bulk GaN epilayers.

**"Spectroscopic studies of GaN grown by metalorganic chemical vapor deposition,"** W. Shan, J. J. Song, T. J. Schmidt, X. H. Yang and B. Goldenberg, TWN Procs. 197, Sept. 21-23 '95, Nagoya, Japan.

We present here our recent results from a variety of spectroscopic investigations of single-crystal GaN epilayers grown on sapphire substrates by MOCVD. The subjects discussed here include effects of temperature and pressure on the band gap of GaN as well as the stimulated emission and lasing phenomena of the MOCVD GaN samples under the conditions of high excitation. Emission lines with the full width at half maximum (FWHM) of  $<1.5$  meV for the intrinsic free excitons and of  $<1.0$  meV for the excitons bound to neutral donors were observed in photoluminescence (PL) spectra taken at 10 K ( Fig. 1). The PL spectra also consist of a broadband emission structure centered in the yellow spectral region and another much weaker broadband emission structure peaked at the blue spectral region. Low-temperature PL of GaN was measured. The exciton emission lines were found to shift almost linearly toward higher energy with increasing pressure. By examining the pressure dependence of the exciton emission structures, the pressure coefficient of the direct  $\Gamma$  band gap in GaN was determined to be  $3.9$  meV/kbar<sup>3</sup>. The value of the hydrostatic deformation potential of the band gap was also deduced from the experimental results to be  $-9.2 \pm 1.2$  eV. The broadband emission band in the yellow spectral region showed a similar behavior under applied pressure to that of exciton emission but with a relatively strong sublinear pressure dependence. The result suggests that the yellow emission band most likely involves the

transitions associated with shallow donors and deep acceptors. The effects of temperature on the interband transitions in GaN were studied to determine the temperature dependence of the GaN band gap. Photoreflectance (PR) spectroscopy measurements were employed in the temperature dependent studies. The sharp derivative-like PR spectral features allowed us to accurately determine the energy value of the fundamental band gap of the GaN at the room temperature (295 K) to be 3.420 eV. Photoluminescence excitation (PLE) and reflectivity measurements showed that well-resolved spectral features associated with exciton transitions in the GaN allow a relatively precise determination of the binding energy for the free excitons, as well as the energy separations between the valence band maxima of the wurtzite GaN. With a carefully designed optical pumping scheme and fine preparation of samples, optically pumped stimulated emission and laser actions were achieved in MOCVD grown GaN sample with bar-like shapes under both picosecond and nanosecond laser excitations. Longitudinal lasing modes could be clearly observe over a broad temperature range from 10 K up to 400 K, and was found to be weakly dependent on temperature. Our results yield a factor of less than two for the increased in the threshold, from  $\sim 500 \text{ kW/cm}^2$  At 10 K to  $\sim 800 \text{ kW/cm}^2$  at room temperature (295K). The shift of the peak position of stimulated emission as a function of temperature was found to differ from that of the GaN band gap. The implications of the results will be discussed.

**"Optical studies of epitaxial GaN based materials," J. J. Song, W. Shan, T. Schmidt, A. J. Fischer, S. J. Hwang, B. Taheri, B. Goldenberg, R. Horning, A. Salvador, W. Kim, O. Akatas, A. Botechkarev and H. Morkoc, SPIE Procds., Jan. 29-Feb. 2 '96, San Jose, CA**

We present the results of optical studies of InGaN alloys grown by MOCVD on top of thick GaN epitaxial layers with sapphire as substrates. Photoluminescence (PL) and photoreflectance (PR) measurements were performed at various temperatures to determine the band gap and its variation as a function of temperature for the samples with different alloy concentrations. We have also studied carrier recombination dynamics using time-resolved luminescence spectroscopy. While the measured decay time for the alloy near-band-edge PL emissions was observed to be generally around 70 ps at 10 K, it was found that the decay time decreased rapidly as the sample temperatures increased. This indicates the strong influence of sample temperature on the processes of trapping and recombination of excited carriers at impurities and defects in the InGaN alloys.

#### **Published Journal Abstracts:**

**"Room-temperature deep-ultraviolet-stimulated emission from  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  thin films grown on sapphire," T. J. Schmidt, Y. H. Cho, J. J. Song, and W. Yang, App. Phys. Lett. 74, 245 (1999).**

Room-temperature deep-ultraviolet-stimulated emission (SE) has been observed from optically pumped metalorganic chemical vapor deposition grown  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  thin films. SE has been observed for Al concentration as high as  $x=0.26$ , with a resultant SE

wavelength as low as 328 nm at room temperature. The results obtained for the  $\text{Al}_x\text{GaN}$  layers are compared with  $\text{In}_x\text{Ga}_{1-x}\text{N}$  layers of comparable alloy concentration and GaN reference layers. The incorporation of Al into layers comparable alloy concentration and GaN reference layers. The incorporation of Al into GaN is shown to result in  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  layers with similar high excitation-density emission behavior as GaN, in contrast to  $\text{In}_x\text{Ga}_{1-x}\text{N}$  layers, which exhibit markedly difference SE behavior. The observation of room-temperature SE from  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  layers of significant Al concentration illustrates the suitability of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  based structures, not only for use in deep-ultraviolet detectors, but also as a potential source of deep-ultraviolet laser radiation.

**"Near-threshold gain mechanisms in GaN thin films in the temperature range of 20-700 K,"** S. Bidnyk, T. J. Schmidt, B. D. Little, and J. J. Song, *App. Phys. Lett.* 74, 1 (1999).

We report the results of an experimental study on near-threshold gain mechanism in optically pumped GaN epilayers in the temperature range of 20-700 K. High-quality singly crystal GaN films grown on 6H-SiC and (0001) sapphire were used in this study. We show that the dominant near-threshold gain mechanism is inelastic exciton-exciton scattering for temperatures below  $\sim 150$  K, characterized by band-filling phenomena and a low stimulated emission (SE) threshold. An analysis of both the temperature dependence of the SE threshold and the relative shift between stimulated and band-edge-related emission indicated electron-hole plasma is the dominant gain mechanism for temperatures exceeding 150 K. Based on our results, we discuss possibilities of reducing the room-temperature lasing threshold in laser diode structures with a GaN active medium.

**"High resolution x-ray analysis of pseudomorphic InGaN/GaN multiple quantum wells: Influence of Si doping concentration,"** Y. H. Cho, F. Fedler, R. J. Haustein, G. H. Park, J. J. Song, S. Keller, U. K. Mishra, and S. P. DenBaars, *Journal of Applied Physics* 85, 3006 (1999).

We report the structural properties of InGaN/GaN/AlGaN multiple quantum wells (MQWs) by means of two-dimensional reciprocal space mapping (RSM) of high resolution x-ray diffraction. The influence of Si doping in GaN barriers on the characteristics has been studied for 12-year period MQWs grown by metalorganic chemical vapor deposition, which have different Si doping concentrations in GaN barriers ranging from  $1 \times 10^{17}$  to  $3 \times 10^{19} \text{ cm}^{-3}$ . Information on the structural quality of these MQWs was extracted from the linewidth broadening of the higher-order superlattice satellite peaks, as well as from the presence of Pendellosung oscillations. The measured diffraction curves were modeled using kinematic diffraction theory. From the symmetric and asymmetric RSMs around (0002), (0004) and (114) reflections, we found that the InGaN/GaN/AlGaN MQWs are grown coherently on the GaN base layer. Better interface properties are achieved with Si doping. Our results indicate that Si doping in the GaN barriers affects the interface quality of the InGaN/GaN MQW systems, and thus, also influences the optical properties.

**"Stimulated emission in GaN thin films in the temperature range of 300-700 K," S. Bidnyk, B. D. Little, T. J. Schmidt, Y. H. Cho, J. Krasinski, J. J. Song, B. Goldenberg, W. Yang, W. G. Perry, M. D. Bremser, and R. F. Davis, Journal of Applied Physics 85, 1792 (1999).**

We report the results of an experimental study on stimulated and spontaneous emission from high-quality singly-crystal GaN films grown on 6H-SiC and (0001) sapphire substrates in the temperature range of 300-700 K. We observed edge-emitted stimulated emission (SE) at temperatures as high as 700 K for samples grown on both SiC and sapphire substrates. The energy position of the SE and spontaneous emission peaks were shown to shift linearly to longer wavelengths with temperature and empirical expressions for the energy positions are given. We demonstrate that the energy separation between the spontaneous and SE peaks gradually increases from 90 meV at 300 K to 200 meV at 700 K indicating that an electron-hole plasma is responsible for the SE mechanism in this temperature range. The temperature sensitivity of the SE threshold for different samples was studied and the characteristic temperature was found to be 173 K in the temperature range of 300-700 K for one of the samples studied. We suggest that the unique properties of SE in GaN thin films at high temperatures could potentially be utilized in optoelectronic devices.

**"Study of stimulated emission in InGaN/GaN multi-quantum wells in the temperature range of 175 K to 575 K," S. Bidnyk, Y. H. Cho, T. J. Schmidt, J. J. Song, S. Keller, U. K. Mishra and S. P. DenBaars, Materials Research Society 512, 199 (1998).**

We present the results of an experimental study on stimulated emission (SE) in optically pumped InGaN/GaN multi-quantum well (MQW) structures in the temperature range of 175 K to 575 K. Samples used in this work consisted of 12 QWs and the GaN barriers were intentionally doped with different Si concentration. The effect of doping on the SE thresholds of the MQWs were investigated. We observed that the SE spectra were comprised of many narrow peaks of less than 1 full width at half maximum (FWHM). No broadening of the FWHMs of the peaks occurred as the temperature was raised from 175 to 575 K. The SE threshold was measured as a function of temperature and compared with that of a thin GaN film. Low SE thresholds were attributed to high quantum efficiency of the MQWs, possibly associated with large carrier localization. A characteristic temperature of 162 K was derived from the temperature dependence of the SE threshold. The integrated emission intensity versus pumping density was examined for different temperatures. This study shows that InGaN/GaN MQWs are suitable for the development of laser diodes that can operate well above room temperature.

**"Laser action in GaN pyramids grown on (111) silicon by selective lateral overgrowth," S. Bidnyk, B. D. Little, Y. H. Cho, J. Krasinski, J. J. Song, W. Yang and S. A. McPherson, Applied Physics Letters 73, 2242 (1998).**

Laser action was observed in GaN pyramids under strong optical pumping at room temperature. The pyramids were laterally overgrown on a patterned GaN/AlN seeding layer grown on a (111) silicon substrate by metal-organic chemical vapor deposition. Each pyramid had a 15- $\mu\text{m}$ -wide hexagonal base and was on average 15  $\mu\text{m}$  in height. The pyramids were individually pumped, imaged, and spectrally analyzed through a high-magnification telescope system using a high-density pulsed excitation source. Under high levels of optical pumping, multimode laser at room temperature was observed. The integrated emission intensity for both spontaneous and lasing peaks was studied as a function of excitation power density. The effects of pyramid geometry and short-pulse excitation on the multimode nature of laser oscillations inside of the pyramids are discussed. This study suggests that GaN microstructures could potentially be used as pixel elements and high-density two-dimensional laser arrays.

**"S-shaped' temperature-dependent emission shift and carrier dynamics in InGaN/GaN multiple quantum wells,"** Y. H. Cho, G. H. Gainer, A. J. Fischer, J. J. Song, S. Keller, U. K. Mishra and S. P. DenBaars, *Applied Physics Letters* **73**, 1370 (1998).

We report temperature-dependent time-integrated and time-resolved photoluminescence (PL) studies of InGaN/GaN multiple quantum wells (MQWs) grown by metalorganic chemical vapor deposition. We observed anomalous emission behavior, specifically an *S-shaped* (decrease-increase-decrease) temperature dependence of the peak energy ( $E_p$ ) for InGaN-related PL with increasing temperature:  $E_p$  redshifts in the temperature range of 10-70 K, blueshifts for 70-150 K, and redshifts again for 150-300 K with increasing temperature. In addition, when  $E_p$  redshifts, the spectra width is observed to narrow, while when  $E_p$  blueshifts, it broadens. From a study of the integrated PL intensity as a function of temperature, it is found that thermionic emission of photocarriers out of local potential minima into higher energy states within the wells is the dominant mechanism leading to the thermal quenching of the InGaN-related PL. We demonstrate that the temperature-induced S-shaped PL shift is caused by change in the carrier dynamics with increasing temperature due to inhomogeneity and carrier localization in the InGaN/GaN MQWs.

**"Energy selective optically pumped stimulated emission from InGaN/GaN multiple quantum wells,"** T. J. Schmidt, Y. H. Cho, G. H. Gainer, J. J. Song, S. Keller, U. K. Mishra and S. P. DenBaars, *Applied Physics Letters* **73**, 560 (1998).

Optically pumped stimulated emission (SE) from InGaN/GaN multiple quantum wells (MQWs) grown by metalorganic chemical vapor deposition has been systematically studied as a function of excitation photon energy ( $E_{exc}$ ) to further understand the origin of SE in these structures. Optically pumped SE was observed for excitation photon energies well below that of the absorption edge of the MQWs, indicating the states responsible for the soft absorption edge in these structures can efficiently couple carriers with the gain region. "Mobility edge" -type behavior in the SE peak was observed as  $E_{exc}$  was varied. The effective mobility edge measured in these SE experiments lies  $\sim 110$  meV above the main spontaneous emission peak and  $\sim 62$  meV above the SE peak. Tuning the excitation

energy below the mobility edge was found to be accompanied by a drastic increase in the SE threshold due to a decrease in the effective absorption cross section. The experimental results indicate that the SE peak observed here has the same microscopic origin as the spontaneous emission peak, i.e., radiative recombination of localized states.

**"Coherent dynamics of excitons in GaN studied by femtosecond four-wave-mixing spectroscopy," A. J. Fischer, W. Shan, J. J. Song, D. S. Kim, D. S. Kim, D. S. Yee, Y. C. Chang, R. Horning, and B. Goldenberg, SPIE 78, 3277 (1998).**

Femtosecond four-wave-mixing (FWM) is used to study the coherent dynamics of excitons in thin epilayers of GaN grown by metalorganic chemical vapor deposition on sapphire substrates. Temperature dependent FWM is used to accurately measure the exciton homogeneous linewidth and it is shown that the excitonic resonances in our samples are shown to be very nearly homogeneously broadened even at low temperatures. We have observed strong beating behavior in the FWM signal corresponding to the energy separation of the A and B free exciton transitions. The beats were studied as a function of relative position across the B exciton and B exciton and not to, so called, polarization interference. The quantum beats were further studied as a function of polarization geometries and a phase shift of  $180^\circ$  was observed when changing from collinear to cross-linear polarization geometries. The FWM signal was calculated in the ultrashort pulse limit in order to theoretically model the observation phase change.

**"High-temperature stimulated emission studies of MOCVD-grown GaN films," S. Bidnyk, B. D. Little, T. J. Schmidt, J. Krasinski and J. J. Song, SPIE 72, 3419 (1998).**

Edge and surface-emitted stimulated emission (SE) in optically pumped GaN thin films was studied in the temperature range of 20 K to 700 K. The single-crystal GaN films used in this work were grown by MOCVD on (0001) sapphire and 6H-SiC substrates. We have observed that the SE peak shifts from 360 nm at 20 K to 412 nm at 700 K, which is the highest temperature at which SE has been reported for this material. The temperature sensitivity of the SE threshold was studied over the entire temperature range. The characteristic temperature was found to be about 170 K over the temperature range of 300 K to 700 K for samples grown on both sapphire and SiC substrates. The energy position of the SE and spontaneous emission peaks were shown to shift linearly to longer wavelengths with increasing temperature and empirical expressions for this shift are given. We demonstrate that the energy separation between the spontaneous and SE peaks gradually increases from 90 meV at 300 to 200 meV at 700 K indicating that an electron-hole plasma is responsible for the SE mechanism above room temperature (RT). We demonstrate that the surface-emitted SE in GaN epilayers comes from cracks, burn spots, and other imperfections, and is due to the scattering of a photon flux propagating parallel to the surface. Our results suggest that these defects are effective scattering centers and, under strong optical excitation, become points of origin for burning of the sample surface. This study shows that GaN has an extremely low temperature sensitivity compared to other semiconductors and is suitable for the development of light emitting devices that can operate significantly above RT.

**"Large optical nonlinearities in the band gap region of GaN thin films grown by MOCVD on sapphire," T. J. Schmidt, Y. C. Chang, and J. J. Song, SPIE 61, 3419 (1998).**

We report the results of nanosecond non-degenerate optical pump-probe experiments and single-beam power dependent absorption experiments performed on metalorganic chemical vapor deposition (MOCVD) grown GaN thin films. Changes in the optical transitions near the band gap due to excess photo-generated free carriers were studied as a function of excitation density at 10K and room temperature using pump-probe spectroscopy. At 10 K, strong, well-resolved features are shown to broaden and decrease in intensity due to the presence of the high densities of photo-excited free carriers generated by the pump beam, resulting in extremely large values of induced transparency, exceeding  $4 \times 10^4 \text{ cm}^{-1}$  as  $I_{\text{exc}}$  was increased to over  $3 \text{ MW/cm}^2$ . In addition, large values of induced absorption are observed with increasing pump density in the below-gap region where gain was expected. This induced absorption was also found to be extremely large, exceeding  $4 \times 10^4 \text{ cm}^{-1}$  as the excitation density  $I_{\text{exc}}$  was increased over  $3 \text{ MW/cm}^2$ . At room temperature the resulting induced transparency and induced absorption were found to approach  $2 \times 10^4 \text{ cm}^{-1}$  as  $I_{\text{exc}}$  approached  $3 \text{ MW/cm}^2$ . The single-beam power dependent absorption experiments show enhanced bleaching of the excitonic transitions with increasing  $I_{\text{exc}}$  compared to the pump-probe experiments, while the below-gap induced absorption is drastically reduced in the single-beam experiments. The large values of induced transparency/absorption observed in this work and the fact that excitons have been shown to persist to over 450 K in GaN<sup>1</sup> (indicating that the large optical nonlinearities will persist substantially above room temperature) suggest the possibility of new opto-electronic applications for the group III nitrides.

**"Near-band-edge photoluminescence emission in  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  under high pressure," W. Shan, J. W. Ager III, W. Walukiewicz, E. E. Haller, B. D. Little, J. J. Song, M. Schurman, Z. C. Feng, R. A. Stall and B. Goldenberg, Applied Physics Letters 72, 2274 (1998).**

We present results of pressure-dependent photoluminescence (PL) studies of single-crystal  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  epitaxial films grown on sapphire substrates by metalorganic chemical vapor deposition. PL measurements were performed under hydrostatic pressure using the diamond-anvil-cell technique. PL spectra taken from the  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  epitaxial films are dominated by strong near-band-edge luminescence emissions. The emission lines were found to shift linearly towards higher energy with increasing pressure. By examining the pressure dependence of the spectral features, the pressure coefficients for the PL emissions associated with the direct  $\pi$  band gap of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  were determined. Our results yield a pressure coefficient of  $4.0 \times 10^{-3} \text{ eV/kbar}$  for  $\text{Al}_{0.05}\text{Ga}_{0.95}\text{N}$  and  $3.6 \times 10^{-3} \text{ eV/kbar}$  for  $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}$ .

**"High-temperature stimulated emission in optically pumped InGaN/GaN multiquantum wells," S. Bidnyk, T. J. Schmidt, Y. H. Cho, G. H. Gainer, J. J. Song, S. Keller, U. K. Mishra and S. P. DenBaars, Applied Physics Letters 72, 1623 (1998).**

Stimulated emission (SE) in optically pumped InGaN/GaN multiquantum well (MQW) structures grown by metalorganic chemical vapor deposition was experimentally studied in the temperature range of 175-575 K. The GaN barriers were intentionally doped with a different Si concentration ranging from  $1 \times 10^{17}$  to  $3 \times 10^{19} \text{ cm}^{-3}$  and the effects of Si doping of GaN barriers on the optical properties of InGaN/GaN MQWs were investigated. The SE threshold was measured as a function of temperature and compared with bulk GaN. We observed that the SE threshold had a low value and a weak temperature dependence: for example,  $\sim 25 \text{ kW/cm}^2$  at 175 K,  $\sim 55 \text{ kW/cm}^2$  at 300 K, and  $\sim 300 \text{ kW/cm}^2$  at 575 K for one of the samples. Low SE thresholds are attributed to the high-quantum efficiency of the MQWs, possibly associated with the large localization of excitons. The characteristic temperature of 162 K was derived from the temperature dependence of the SE threshold. The integrated emission intensity versus pumping density was examined for different temperatures. This study shows that InGaN/GaN MQWs are suitable for development of laser diodes that can operate well above room temperature.

**"Optical Properties of In<sub>x</sub>Ga<sub>1-x</sub>N alloys grown by metalorganic chemical vapor action,"** W. Shan, W. Walukiewicz, E. E. Haller, B. D. Little, J. J. Song, M. D. McCluskey, N. M. Johnson, Z. C. Feng, M. Shurman, and R. A. Stall, *Journal of Applied Physics* 84, 4452 (1998).

We present the results of optical studies of the properties of In<sub>x</sub>Ga<sub>1-x</sub>N epitaxial layers ( $0 < x < 0.2$ ) grown by metalorganic chemical vapor deposition. The effects of the alloying on the fundamental gap of In<sub>x</sub>Ga<sub>1-x</sub>N were investigated using a variety of spectroscopic techniques. The fundamental band-gap energies of the In<sub>x</sub>Ga<sub>1-x</sub>N alloys were determined using photomodulation spectroscopy measurements and the variation of the fundamental band gap for the In<sub>x</sub>Ga<sub>1-x</sub>N samples with the different alloy concentrations were examined by studying the shift of photoluminescence (PL) emission lines using the diamond-anvil pressure-cell technique. The results show that PL originates from effective-mass conduction-band states. Anomalous temperature dependence of the PL peak shift and linewidth as well as the Stokes shift between photoreflectance and PL lines is explained by composition fluctuations in as-grown InGaN alloys.

**"Intrinsic exciton transitions in GaN,"** W. Shan, A. J. Fischer, S. J. Hwang, B. D. Little, R. J. Hauenstein, X. C. Xie, J. J. Song, D. S. Kim, B. Goldenberg, R. Horning, S. Krishnankutty, W. G. Perry, M. D. Bremser and R. F. Davis, *Journal of Applied Physics* 83, 455 (1998).

Intrinsic excitonic transitions in GaN have been studied using a variety of spectroscopic measurements. Sharp spectral structures associated with intrinsic free excitons could be observed in photoluminescence, reflection, and absorption spectra. The energy positions of excitonic transitions in GaN epitaxial layers were found to be influenced by the residual strain resulting from lattice-parameter and thermal-expansion mismatches between the epilayers and the substrates. The values of the four principal deformation potentials of wurtzite GaN were derived by using the strain tensor components



determined by x-ray measurements. The observation of spectral features involving the emission of LO phonons in absorption and photoluminescence excitation spectra at energies above exciton resonances indicate that a phonon-assisted indirect excitation process, which simultaneously generates a free exciton and a LO phonon, is a very significant and efficient process in GaN. The lifetime of the free excitons is found to be longer than the relaxation time of LO-phonon emission but much shorter than that of acoustic-phonon emission.

**"Large optical nonlinearities near the band gap of GaN thin films," T. J. Schmidt, J. J. Song, Y. C. Chang, R. Horning and B. Goldenberg, Journal of Applied Physics 72, 1504 (1998).**

The interband optical transitions in single-crystal GaN films grown by metal organic chemical vapor deposition have been studied at 10 K and room temperature using nondegenerate nanosecond optical pump-probe techniques. At low temperatures, strong, well-resolved features are seen in the absorption and reflection spectra corresponding to the 1 s A and B exciton transitions. These features broaden and decrease in intensity due to the presence of a high density of photoexcited free carriers and are completely absent in the absorption and reflection spectra as the excitation density,  $I_{exc}$ , approaches 3 MW/cm<sup>2</sup>, resulting in induced transparency in transmission measurements. The absorption spectra also show induced absorption below the band gap as  $I_{exc}$  is increased. Both the observed induced transparency and induced absorption were found to be extremely large, exceeding  $4 \times 10^4$  cm<sup>-1</sup> as the pump density approaches 3 MW/cm<sup>2</sup> at 10K.

**"Excitation energy-dependent optical characteristics of InGaN/GaN multiple quantum wells," Y. H. Cho, J. J. Song, S. Keller, U. K. Mishra, and S. P. DenBaars; Applied Physics Letters 73, 3181 (1998).**

We have systematically studied the optical properties of InGaN/GaN multiple quantum wells (MQWs) at 10 K under different excitation conditions using photoluminescence (PL), PL excitation, and time-resolved PL spectroscopy. We found that the PL emission consists of a strong main peak at 2.80 eV and a much weaker and broader secondary peak at ~2.25 eV. We observed that the peak position blueshifts and the spectral width narrows for the main peak when the excitation energies varied from the 3.81 eV (above the band gap of the AlGaIn capping layer) to 2.99 eV (below the band gap of the GaN barrier layers). The intensity ratio of the main peak to the secondary peak also varied with excitation energy. The two observed emission peaks from different layers of the MQWs. Time-integrated and time-resolved PL revealed that the InGaIn-related spontaneous emission processes are strongly affected by inhomogeneity and carrier localization in the MQWs. From these studies under varying excitation energies, we conclude that interface-related defects and roughness may play an important role in the InGaIn-related emission mechanism during the carrier transfer between different layers of the MQWs.

**"Pump-probe spectroscopy of band tail states in metalorganic chemical vapor deposition-grown InGaN,"** T. J. Schmidt, Y. H. Cho, G. H. Gainer, and J. J. Song S. Keller, U. K. Mishra, and S. P. DenBaarr, *Applied Physics Letters* 73, 1892 (1998).

Nanosecond nondegenerate optical pump-probe experiments have been performed on InGaN thin films and InGaN/GaN multiple quantum wells. Bleaching of absorption of the localized band tail states was observed with increasing excitation density ( $I_{exc}$ ) of the pump pulse. The dynamics of the bleaching was found to depend on the localization depth of the band tail states and on  $I_{exc}$ . With high  $I_{exc}$ , large blueshifts in the spontaneous emission luminescence peaks were also observed, the magnitude of which was again found to depend on the localization depth of the band tail states. Stimulated emission is observed from the samples with increasing  $I_{exc}$  and correlates with significant changes in the behavior of the absorption bleaching. The observed bleaching dynamics of the band tail states are well explained by considering the effective lifetime of the band tail states as measured by time-resolved photoluminescence experiments.

**"Influence of Si doping on characteristics of InGaN/GaN multiple quantum wells,"** Y. H. Cho, J. J. Song, S. Keller, M. S. Minsky, E. Hu, U. K. Mishra, and S. P. DenBaars *Applied Physics Letters* 73, 1128 (1998)

We have systematically studied the influence of Si doping on the characteristics of InGaN/GaN multiple quantum wells (MQWs) by means of high-resolution x-ray diffraction (HRXRD), photoluminescence (PL), PL excitation (PLE), and time-resolved PL spectroscopy. The twelve-period MQWs were grown by metalorganic chemical vapor deposition. Si doping in the GaN barriers was varied from  $1 \times 10^{17}$  to  $3 \times 10^{19} \text{ cm}^{-3}$ . Information on the structural quality of the MQWs as a function of Si doping was extracted from the linewidth broadening of the higher-order superlattice satellite peaks measured in HRXRD. The HRXRD measurements indicate that increased Si doping results in better interface properties of the MQWs. PL and PLE measurements show a decrease in the Stokes shift with increasing Si doping concentration. The 10 K radiative recombination lifetime was observed to decrease from  $\sim 30 \text{ ns}$  (for  $n < 1 \times 10^{17} \text{ cm}^{-3}$ ) to  $\sim 4 \text{ ns}$  (for  $n = 3 \times 10^{19} \text{ cm}^{-3}$ ) with increasing Si doping concentration. The reduced Stokes shift, the decrease in radiative recombination lifetime, and the increase in the interface quality indicate that Si doping results in a decrease in carrier localization at potential fluctuations in the InGaN active layers.

**"Stimulated emission characteristics of InGaN/GaN multiple quantum wells: Excitation length and excitation density Dependence,"** T. J. Schmidt, S. Bidnyk, Yong-Hoon Cho, A. J. Fischer, J. J. Song, S. Keller, U. K. Mishra, S. P. DenBaars, *Applied Physics Letters* 73, 3689 (1998).

Optically pumped stimulated emission (SE) from InGaN/GaN multiple quantum wells (MQWs) grown by metalorganic chemical vapor deposition has been systematically studied as a function of excitation length ( $L_{exc}$ ). Two distinct SE peaks were observed from these structures: one that originates at 425 nm at 10 K (430 nm at 300 K) and another that originates at 434 nm at 10 K (438 nm at 300 K). The SE threshold for the

high-energy peak was observed to always be lower than that of the low-energy peak, but the difference was found to decrease greatly with increasing  $L_{exc}$ . A detailed study of the emission intensity of these two SE peaks as a function of excitation density shows that the two peaks compete for gain in the MQW active region.

**"Temperature-dependent absorption measurements of excitons in GaN epilayers,"** A. J. Fischer, W. Shan, J. J. Song, Y. C. Chang, R. Horning and B. Goldenberg, *Applied Physics Letters* 71, 1981 (1997).

Optical absorption measurements were performed on a series of thin GaN epilayers. Sharp spectral features were observed due to the  $1s A$  and  $B$  exciton transitions. Using polarization dependent absorption, the  $C$  exciton transition was identified. A broad absorption feature was observed at  $\sim 3.6$  eV, which is attributed to indirect exciton-phonon absorption. The excitonic structure was found to persist well above room temperature. A fit to the Varshni formula yielded a temperature dependence of  $E(T) = E(T=0) - 11.8 \times 10^{-4} T^2 (1414 + T)$  eV for the  $A$  and  $B$  excitons. The exciton absorption linewidth was studied as a function of temperature, indicating that GaN exhibits very large exciton-phonon coupling.

**"Strain effects on excitonic transitions in GaN,"** A. J. Fischer, J. J. Song, W. G. Perry, M. D. Bremser, R. G. Davis, and B. Goldenberg, *Mat. Res. Symp. Proc.* 449, 841 (1997).

We present the results of experimental studies of the strain effects on the excitonic transitions in GaN epitaxial layers on sapphire and SiC substrates. Photoluminescence and reflectance spectroscopies were performed to measure the energy positions of exciton transitions and X-ray diffraction measurements were conducted to examine the lattice parameters of GaN epitaxial layers grown on different substrates. Residual strain induced by the mismatch of lattice constants and thermal-expansion between GaN epitaxial layers and substrates was found to have a strong influence in determining the energies of excitonic transitions. The overall effect of the strain generated in GaN is compressive for GaN grown on sapphire and tensile for GaN on SiC substrate. The uniaxial and hydrostatic deformation potentials of wurtzite GaN were derived from the experimental results. Our results yield the uniaxial deformation potentials  $b_1 \approx -5.3$  eV and  $a_2 \approx -11.8$  eV.

**"Optical studies of MOCVD in  $In_xGa_{1-x}N$  alloys,"** B. D. Little, W. Shan, J. J. Song, Z. C. Feng, M. Schurman and R. A. Stall, *Mat. Res. Soc. Symp.* 449, 823 (1997).

We present the results of optical studies of  $In_xGa_{1-x}N$  alloys ( $0 < x < 0.2$ ) grown by metalorganic chemical vapor deposition on top of thick GaN epitaxial layers with sapphire as substrates. Photoluminescence (PL) and photoreflectance (PR) measurements were performed at various temperatures to determine the band gap and its variation as a function of temperature for samples with different indium concentrations. Carrier recombination dynamics in the alloy samples were studied using time-resolved luminescence spectroscopy. While the measured decay time for the alloy near-band-edge

PL emissions was observed to be generally around a few hundred picoseconds at 10K, it was found that the decay time decreased rapidly as the sample temperatures increased. This indicates a strong influence of temperature on the processes of trapping and recombination of excited carriers at impurities and defects in the InGaN alloys.

**"Optical processes in GaN and its related heterostructures," J. J. Song, A. J. Fischer, T. J. Schmidt, S. Bidnyk and W. Shan, Nonlinear Optics 18, 269 (1997).**

We present the results of a study on the optical properties of GaN and related heterostructures using a variety of spectroscopic methods including optical pumping and four-wave-mixing. The residual strain was found to play an important role in determining the energy positions of excitonic transitions. Combined with high-precision X-ray measurements, the four principal deformation potentials were derived. Optical pumping was performed to study the effects of sample imperfections on the stimulated emission in both back-scattering and edge emission geometries. Coherent optical properties of excitons in GaN are studied using femtosecond four-wave-mixing. Quantum beating between the A and B free excitons has been observed and is studied as a function of polarization geometry.

**"Dynamics of photoexcited carriers in  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  double heterostructures," W. Shan, S. Xu, B. D. Little, X. C. Xie, J. J. Song, G. E. Bulman, H. S. Kong, M. T. Leonard and S. Krishnakutty, Journal of Applied Physics 82, 3158 (1997).**

We present the results of a time-resolved photoluminescence study of the dynamics of photoexcited carriers in  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  double heterostructures (DHs). The carrier dynamics including generation, diffusion, spontaneous recombination, and nonradiative relaxation were studied by examining the time decay of photoluminescence associated with the spontaneous recombination from the samples. The temporal evolution of the luminescence from the GaN active layers of the DH samples was found to be governed by a carrier-diffusion dominated capture process. The determination of the capture time for the carriers drift and diffusion into the GaN active region, in addition to the effective lifetimes of the spontaneous recombination for carriers in the AlGa<sub>N</sub> cladding layers and the GaN active region, allows an estimation of the diffusion constants for the minority carriers in the  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  cladding layers of the DRs. Our results yield a diffusion constant of 2.6 cm<sup>2</sup>/s for  $\text{Al}_{0.03}\text{Ga}_{0.97}\text{N}$  and 1.5 cm<sup>2</sup>/s for  $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$  at 10 K.

**"Study of surface-emitted stimulated emission in GaN," S. Bidnyk, T. J. Schmidt, G. H. Park and J. J. Song, Applied Physics Letters, 71, 729 (1997).**

We report the results of a study of spatially resolved surface-emitted stimulated emission in GaN epilayer samples under conditions of strong optical pumping. We observe that even at excitation powers near the damage threshold, no surface-emitted stimulated emission occurs from samples with a high-quality GaN epilayer. In parts of the samples with inferior surface quality, we show that stimulated emission comes from cracks, burned spots, and other imperfections, and is due to the scattering of a photon flux

propagating parallel to the surface. Our results suggest that these defects are effective scattering centers and can severely affect the accuracy of optical gain measurements.

**"Femtosecond four-wave-mixing studies of nearly homogeneously broadened excitons in GaN,"** A. J. Fischer, W. Shan, G. H. Park, J. J. Song, D. S. Kim, D. S. Yee, R. Horning and B. Goldenberg, *Phys. Rev. B* 56, 1077 (1997).

Femtosecond degenerate four-wave-mixing (FWM) is used to study coherent dynamics of excitons in GaN epilayers. Spectrally resolved (SR) FWM data are dominated by the *A* and *B* intrinsic excitonic resonances. SR FWM combined with time-integrated (TI) FWM demonstrates that the excitonic resonances are nearly homogeneously broadened even at low temperature. The temperature-dependent dephasing rate is used to deduce exciton-phonon interaction rates. TI FWM shows a strong beating between the *A* and *B* excitons and the beats are shown to be true quantum beats. In addition, a 180° phase shift in the quantum beating was observed when the polarization geometry was changed from collinear to cross-linear.

**"Correlation of Biaxial Strains, Bound Exciton Energies, and Defect Microstructures in GaN Films Grown on AlN/6H-SiC(0001) Substrates,"** W. G. Perry, T. Zheleva, M. D. Bremser, R. F. Davis, W. Shan and J. J. Song, *Journal of Electronic Materials* 26, 224 (1997).

Biaxial strains resulting from mismatches in thermal expansion coefficients and lattice parameters in 22 GaN films grown on AlN buffer layers previously deposited on vicinal and on-axis lattice parameter. A Poisson's ratio of  $\nu = 0.18$  was calculated. The bound exciton energy ( $E_{BX}$ ) was a linear function of these strains. The shift in  $E_{BX}$  with film stress was 23 meV/Gpa. Threading dislocations densities of  $\sim 10^8/\text{cm}^2$  were determined for GaN films grown on vicinal and on-axis SiC, respectively. A 0.9% residual compressive strain at the GaN/AlN interface was observed by high resolution transmission electron microscopy (HRTEM).

**"Pressure -dependent Photoluminescence study of  $\text{In}_x\text{Ga}_{1-x}\text{N}$ ,"** W. Shan, J. J. Song, Z. C. Feng, M. Schurman and R. A. Stall, *Journal of Applied Physics* 71, 2433 (1997).

We present the results of pressure-dependent photoluminescence (PL) studies of single-crystal  $\text{In}_x\text{Ga}_{1-x}\text{N}$  ( $0 \leq x < 0.15$ ) films grown on top of thick GaN epitaxial layers by metalorganic chemical vapor deposition with sapphire as substrates. PL measurements were performed at 10 K as a function of applied hydrostatic pressure using the diamond-anvil-cell technique. The luminescence emission from the  $\text{In}_x\text{Ga}_{1-x}\text{N}$  epilayers were found to shift linearly toward higher energy with increasing pressure. By examining the pressure dependence of the PL spectra, the pressure coefficients for the emission structures associated with the direct band gap of  $\text{In}_x\text{Ga}_{1-x}\text{N}$  were determined. The values of the pressure coefficients were found to be  $3.9 \times 10^{-3}$  eV/kbar for  $\text{In}_{0.08}\text{Ga}_{0.92}\text{N}$  and  $3.5 \times 10^{-3}$  eV/kbar for  $\text{In}_{0.14}\text{Ga}_{0.86}\text{N}$ .

**"Linear and Nonlinear Optical Investigations of GaN and AlGa<sub>N</sub>/GaN Heterostructures," J. J. Song, A. J. Fischer, W. Shan, B. Goldenberg, and G. E. Bulman, *Inst. Phys. Conf. Ser. No. 155*, 355, (1997).**

We present the results of a series of studies on the optical properties of GaN and AlGa<sub>N</sub>/GaN heterostructures using a variety of spectroscopic techniques. Strain effects were found to have a strong influence in determining the energies of excitonic transitions. The observations of spectral features associated with the transitions involving the ground and excited exciton states make it possible to directly estimate binding energy for the excitons in GaN. Optical pumping experiments were performed on AlGa<sub>N</sub>/GaN separate confinement heterostructures (SCH) grown on sapphire by MBE and on SiC by MOCVD. The threshold pumping powers were found to be an order of magnitude lower than that for regular GaN epilayers. Nonlinear four-wave-mixing experiments were carried out in both femtosecond and picosecond regimes to study the intensity and time response of scattering efficiency, as well as the pump-induced nonlinear refractive index change.

**"Bound Exciton Energies, Biaxial Strains, and Defect Microstructures in GaN/AlN/6H-SiC(0001) Heterostructures," W. G. Perry, T. Zheleva, K. J. Linthicum, M. D. Bremser, R. F. Davis, W. Shan and J. J. Song, *Materials Research Society* 449, 847 (1997).**

Biaxial strains resulting from mismatches in thermal expansion coefficients and lattice parameters in 22 GaN films grown on AlN buffer layers previously deposited on vicinal and on-axis 6H-SiC(0001) substrates were measured via changes in the c-axis parameter (*c*). Six of the films were in compression, indicating the residual strain due to lattice mismatch was not relieved. A Poisson's ratio of  $\nu=0.18$  was calculated. The bound exciton energy ( $E_{BX}$ ) was a linear function of these strains. The shift in  $E_{BX}$  with film stress was 23 meV/GPa. The role of the SiC off-axis tilt was investigated for GaN films grown concurrently on the vicinal and on-axis 6H-SiC substrates. Marked variations in  $E_{BX}$  and *c* were observed, with a maximum shift of  $\Delta E_{BX} = 15$  meV and  $\Delta c = 0.0042$  Å. Threading dislocation densities of  $\sim 10^{10}/\text{cm}^2$  and  $\sim 10^8/\text{cm}^2$  were determined for GaN films grown on vicinal and on-axis SiC, respectively. A 0.9% residual compressive strain at the GaN/AlN interface was observed by high resolution transmission electron microscopy (HRTEM). It is proposed that the on-axis SiC substrate does not offer a sufficient density of steps for defect formation to relieve the lattice mismatch between GaN and AlN and AlN and SiC.

**"Optical Transitions in In<sub>x</sub>Ga<sub>1-x</sub>N Alloys Grown by Metalorganic Chemical Vapor Deposition", W. Shan, B. Little, and J. J. Song, Z. C. Feng, M. Schurman, and R. A. Stall, *Applied Physics Letters* 69, 3315 (1996).**

We present the results of optical studies of In<sub>x</sub>Ga<sub>1-x</sub>N alloys ( $0 < x < 0.2$ ) grown by metalorganic chemical vapor deposition on top of thick GaN epitaxial layers with sapphire as substrates. Photoluminescence (PL) and photorefectance measurements were performed at various temperatures to determine the band gap and its variation as a

function of temperature for samples with different indium concentrations. Carrier recombination dynamics in the alloy samples were studied using time-resolved luminescence spectroscopy. While the measured decay time for the alloy near-band-edge PL emissions was observed to be generally around a few hundred picoseconds at 10 K, it was found that the decay time decreased rapidly as the sample temperatures increased. This indicates a strong influence of temperature on the processes of trapping and recombination of excited carriers at impurities and defects in the InGaN alloys.

**"Room-temperature stimulated emission in GaN/AlGaIn separate confinement heterostructures grown by molecular beam epitaxy," T. J. Schmidt, X. H. Yang, W. Shan, and J. J. Song, A. Salvador, W. Kim, Ö. Aktas, A. Botchkarev, and H. Morkoç, Applied Physics Letters 68,1820 (1996).**

Strong near-ultraviolet stimulated emission was observed at room temperature in GaN/AlGaIn separate confinement heterostructures (SCH) grown by molecular beam epitaxy (MBE) on sapphire substrates. The MBE grown GaN/AlGaIn SCH samples exhibited stimulated emission threshold pumping powers as low as  $90 \text{ kW/cm}^2$  at room temperature under the excitation of a frequency-tunable nanosecond laser system with a side-pumping configuration. This represents an order of magnitude reduction over bulklike GaN. Our results suggest that the carrier confinement and waveguiding effects of the SCH samples result in a substantial decrease in the stimulated emission threshold.

**"Binding Energy for the Intrinsic Excitons in Wurtzite GaN", W. Shan, B. D. Little, A. J. Fischer, J. J. Song, B. Goldenberg, W. G. Perry, M. D. Bremser, and R. F. Davis, Phys. Rev. B 54, 16369 (1996).**

We present the results of an experimental study on the binding energy for intrinsic free excitons in wurtzite GaN. High-quality single-crystal GaN films grown by metalorganic chemical vapor deposition were used in this study. Various excitonic transitions in GaN were studied using reflectance measurements. The observation of a series of spectral features associated with the transitions in GaN were studied using reflectance measurements. The observation of a series of spectral features associated with the transitions involving the ground and excited exciton states allows us to make a straightforward estimate of exciton binding energy using the hydrogenic model. Our results yield a binding energy  $E_b=0.021\pm0.001 \text{ eV}$  for the A and B excitons, and  $0.023\pm0.001 \text{ eV}$  for the C exciton in wurtzite GaN within the framework of the effective mass approximation.

**"Optical Studies of GaN and GaN/AlGaIn Heterostructures on SiC Substrates", W. Shan, A. J. Fischer, J. J. Song, G. E. Bulman, H. S. Kong, M. T. Leonard, W. G. Perry, M. D. Bremser, and R. F. Davis, Journal of Applied Physics 69, 740 (1996).**

We present the results of spectroscopic studies on GaN based epitaxial materials on SiC substrates by metalorganic chemical vapor deposition. A variety of techniques has been used to study the optical properties of GaN epilayers and GaN/AlGaIn heterostructures. Sharp spectral structures associated with the intrinsic free excitons were observed by photoluminescence and reflectance measurements from GaN based materials grown on

SiC substrates. The residual strain was found to have a strong influence in determining the energies of exciton transitions. Picosecond relaxation studies of exciton decay dynamics suggest that an AlGa<sub>N</sub> cladding layer with a small mole fraction of AlN can be relatively effective in enhancing the radiative recombination rate for excitons by reducing the density of dislocations and suppressing surface recombination velocity in the GaN active layer for the GaN/AlGa<sub>N</sub> heterostructure samples.

**"Optical Properties of Mg-GaN, GaN/AlGa<sub>N</sub> SCH structures, and GaN on ZnO Substrates", H. Morkoc, W. Kim, O. Aktas, A. Salvador, A. Botchkarev, D. C. Reynolds, M. Smith, G. D. Chen, J. Y. Lin, H. X. Jiang, T. J. Schmidt, X. H. Yang, W. Shan, J. J. Song, B. Goldenberg, C. W. Litton, and K. Evans, Mat. Res. Soc. Symp. Proc. 395, 527 (1996).**

GaN films and GaN/AlGa<sub>N</sub> heterostructures have been grown by MBE. GaN films doped with varying levels of Mg indicate effective mass acceptor at low doping concentrations, as determined from strong photoluminescence emission at about 380nm. As the Mg concentration is increased the photoluminescence emission line red shifts considerably, indicating the formation of Mg-related or induced complexes whose lifetimes are relatively short. GaN/AlGa<sub>N</sub> separate confinement heterostructures grown on sapphire show strong near ultraviolet stimulated emission at room temperature in a side-pumping configuration. The pumping threshold for stimulated emission at room temperature was found to be  $\sim 90 \text{ kW/cm}^2$ . Initial GaN films grown on ZnO substrates show the A exciton in low temperature photoluminescence. ZnO is being considered for nitride growth because of its stacking order and close lattice match.

**"Optical Studies of Epitaxial GaN Based Materials", J. J. Song, W. Shan, T. Schmidt, X. H. Yang, A. Fischer, S. J. Hwang, B. Taheri, B. Goldenberg, R. Horning, A. Salvador, W. Kim, O. Aktas, A. Botchkarev, and H. Morkoc, SPIE Proceedings 86, 2693 (1996).**

A variety of spectroscopic techniques have been used to study the optical properties of epitaxial GaN based materials grown by metalorganic chemical vapor deposition and molecular beam epitaxy. The emphasis was on the issues vital to device applications such as stimulated emission and laser action, as well as carrier relaxation dynamics. Sharp exciton structures were observed by optical absorption measurements above 300 K, providing direct evidence of the formation of excitons in GaN at temperatures higher than room temperature. Using a picosecond streak camera, the time decay of free and bound exciton emissions was studied. By optical pumping, stimulated emission and lasing were investigated over a wide temperature range up to 420 K. In addition, the optical nonlinearity of GaN was studied using wave-mixing techniques.

**"Recent Progress in Optical Studies of Wurtzite GaN Grown by Metalorganic Chemical Vapor Deposition", W. Shan, T. Schmidt, X. H. Yang, J. J. Song, and B. Goldenberg, Inst. Phys. Conf. Ser. 145, 1151 (1996).**



We present the recent results of our spectroscopic studies on optical properties of GaN grown by metalorganic chemical vapor deposition including the issues vital to device applications such as stimulated emission and laser action, as well as carrier relaxation dynamics. By optical pumping, stimulated emission and lasing were investigated over a wide temperature range up to 420 K. Using a picosecond streak camera, free and bound exciton emission decay times were measured. In addition, the effects of pressure on the optical interband transitions and the transitions associated with impurity/defect states were studied using diamond-anvil pressure-cell technique.

**"Optical Properties of Wurzite GaN Grown by Low-pressure Metalorganic Chemical-Vapor Deposition", W. Shan, T. Schmidt, X. H. Yang, J. J. Song, and B. Goldenberg, Journal Applied Physics 79, 3691 (1996).**

We present the results of optical studies on the properties of GaN grown by low-pressure metalorganic chemical vapor deposition, with emphasis on the issues vital to device applications such as stimulated emission and laser action as well as carrier relaxation dynamics. By optical pumping, a stimulated emission and lasing were investigated over a wide temperature range up to 420 K. Using a picosecond streak camera, the free and bound exciton emission decay times were examined. In addition, the effects of temperature and pressure on the optical interband transitions and the transition associated with impurity/defect states were studied using a variety of spectroscopic methods, including photoluminescence and photoreflectance. The fundamental band gap of GaN was mapped out as a function of temperature using the empirical Varshni relation. The pressure coefficient of the gap was determined using diamond-anvil pressure-cell technique. The hydrostatic deformation potential for the direct  $\Gamma$  band gap was also derived from the experimental results.

**"Optical transitions in  $\text{In}_x\text{Ga}_{1-x}\text{N}$  alloys grown by metalorganic chemical vapor deposition," W. Shan, B. D. Little, J. J. Song, Z. C. Feng, M. Schurman, and R. A. Stall, Applied Physics Letters, 69, 3315 (1996).**

We present the results of optical studies of  $\text{In}_x\text{Ga}_{1-x}\text{N}$  alloys ( $0 < x < 0.2$ ) grown by metalorganic chemical vapor deposition on top of thick GaN epitaxial layers with sapphire as substrates. Photoluminescence (PL) and photoreflectance measurements were performed at various temperatures to determine the band gap and its variation as a function of temperature for samples with different indium concentrations. Carrier recombination dynamics in the alloy samples were studied using time-resolved luminescence spectroscopy. While the measured decay time for the alloy near-band-edge PL emissions was observed to be generally around a few hundred picoseconds at 10 K, it was found that the decay time decreased rapidly as the sample temperatures increased. This indicates a strong influence of temperature on the processes of trapping and recombination of excited carriers at impurities and defects in the InGaN alloys.

**"Optical Studies of GaN and GaN/AlGaN Heterostructures on SiC Substrates", W. Shan, A. J. Fischer, J. J. Song, G. E. Bulman, H. S. Kong, M. T. Leonard, W. G. Perry, M. D. Bremser, and R. F. Davis, Journal of Applied Physics 69, 740 (1996).**

We present the results of spectroscopic studies on GaN based epitaxial materials on SiC substrates by metalorganic chemical vapor deposition. A variety of techniques has been used to study the optical properties of GaN epilayers and GaN/AlGaIn heterostructures. Sharp spectral structures associated with the intrinsic free excitons were observed by photoluminescence and reflectance measurements from GaN based materials grown on SiC substrates. The residual strain was found to have a strong influence in determining the energies of exciton transitions. Picosecond relaxation studies of exciton decay dynamics suggest that an AlGaIn cladding layer with a small mole fraction of AlN can be relatively effective in enhancing the radiative recombination rate for excitons by reducing the density of dislocations and suppressing surface recombination velocity in the GaN active layer for the GaN/AlGaIn heterostructure samples.

**"Picosecond Four-Wave-Mixing in GaN Epilayers at 532 nm", B. Taheri, J. Hays, J. J. Song, and B. Goldenberg, Applied Physics Letters 68, 1 (1996).**

Pulsed probe degenerate four wave mixing experiments were performed on GaN epilayers using 13 ps pulses at 532 nm. Intensity and time response of the scattering efficiency was studied. Intensity dependence of the observed signal suggests carrier generation by both single and two photon effects. The absolute scattering efficiency was measured and related to pump-induced nonlinear index change. The nonlinear refractive coefficient found was  $1 \times 10^3 \text{ cm}^2/\text{GW}$  which is greater than an order of magnitude larger than the expected value. Time response of the signal was found to be dictated by carrier lifetimes. Double-exponential decays to trap levels with lifetimes of 100 ps and 1.1 ns are suggested as the dominant recombination processes.

**"Strain Effects on Excitonic Transitions in GaN: Deformation Potentials", W. Shan, R. J. Hauenstein, A. J. Fischer, and J. J. Song, W. G. Perry, M. D. Bremser, R. F. Davis, and B. Goldenberg, Phys. Rev. B 54, 13460 (1996).**

We present the results of experimental studies of the strain effects on the excitonic transitions in GaN epitaxial layers on sapphire and SiC substrates, with the emphasis on the determination of deformation potentials for wurtzite GaN. Photoluminescence and reflectance spectroscopies were performed to measure the energy positions of exciton transitions and x-ray diffraction measurements were conducted to examine the lattice parameters of GaN epitaxial layers grown on different substrates. Residual strain induced by the mismatch of lattice constants and thermal expansion between GaN epitaxial layers and substrates was found to have a strong influence in determining the energies of excitonic transitions. The overall effects of the strain generated in GaN are compressive for GaN grown on sapphire and tensile for GaN on SiC substrate. The uniaxial and hydrostatic deformation potentials of wurtzite GaN were derived from the experimental results. Our results yield the uniaxial deformation potentials  $b_2 \approx -5.3 \text{ eV}$  and  $b_2 \approx -2.7 \text{ eV}$ , as well as the hydrostatic components  $a_1 \approx -6.5 \text{ eV}$  and  $a_2 \approx -11.8 \text{ eV}$ .

**"Optical transitions in  $\text{In}_x\text{Ga}_{1-x}\text{N}$  alloys grown by metalorganic chemical vapor deposition," W. Shan, B. D. Little, J. J. Song, Z. C. Feng, M. Schurman, and R. A. Stall, Applied Physics Letters, 69, 3315 (1996).**

We present the results of optical studies of  $\text{In}_x\text{Ga}_{1-x}\text{N}$  alloys ( $0 < x < 0.2$ ) grown by metalorganic chemical vapor deposition on top of thick GaN epitaxial layers with sapphire as substrates. Photoluminescence (PL) and photorefectance measurements were performed at various temperatures to determine the band gap and its variation as a function of temperature for samples with different indium concentrations. Carrier recombination dynamics in the alloy samples were studied using time-resolved luminescence spectroscopy. While the measured decay time for the alloy near-band-edge PL emissions was observed to be generally around a few hundred picoseconds at 10 K, it was found that the decay time decreased rapidly as the sample temperatures increased. This indicates a strong influence of temperature on the processes of trapping and recombination of excited carriers at impurities and defects in the InGaN alloys.